Neutrino Physics
and
Nuclear astrophysics

Lecture III – gravitational collapse supernovae

National Nuclear Physics Summer School

St. Johns College, Santa Fe, NM, July 2012

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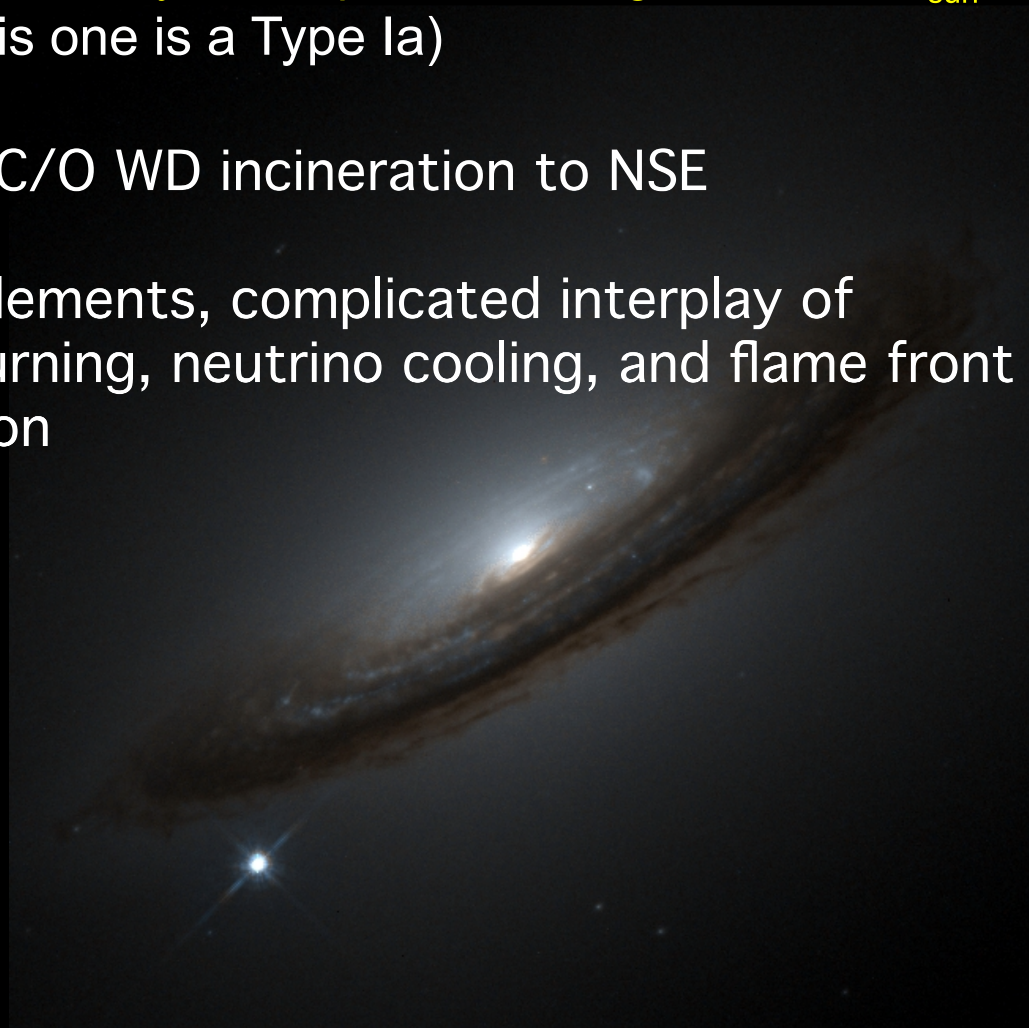
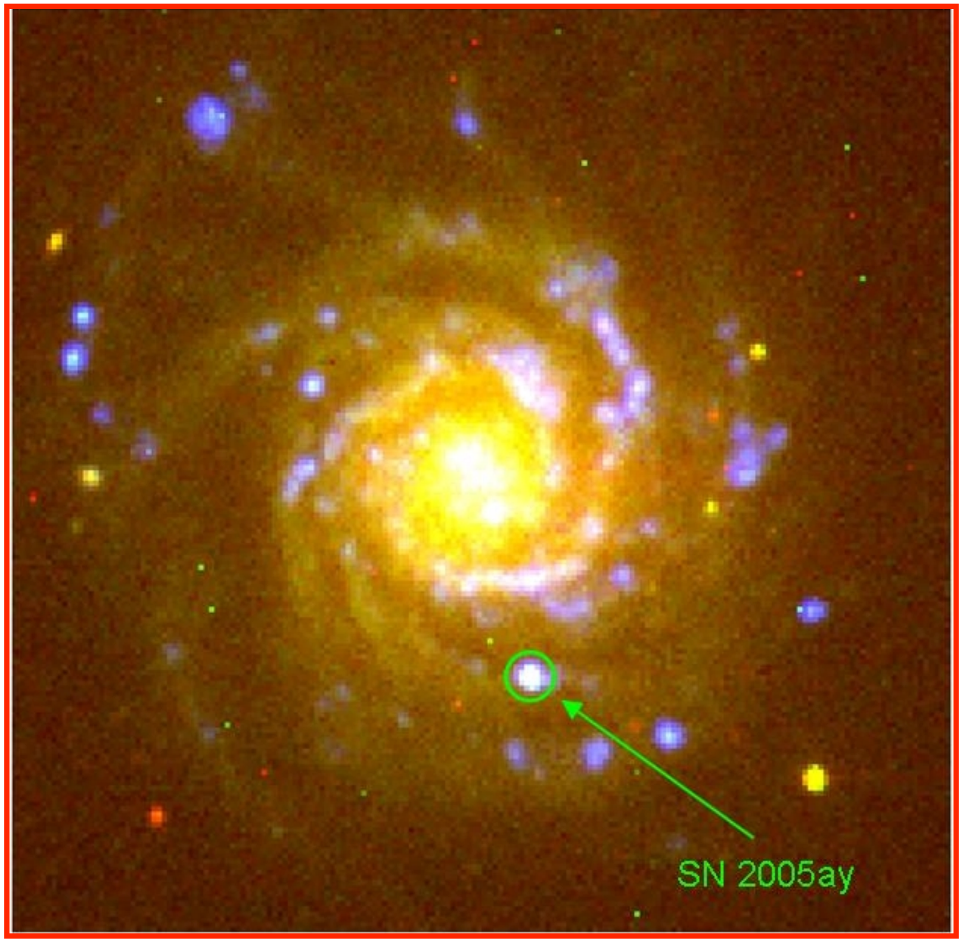
Photon luminosity of a supernova is huge: $L \sim 10^{10} L_{sun}$
(this one is a Type Ia)

Type Ia – C/O WD incineration to NSE

Fe-peak elements, complicated interplay of nuclear burning, neutrino cooling, and flame front propagation



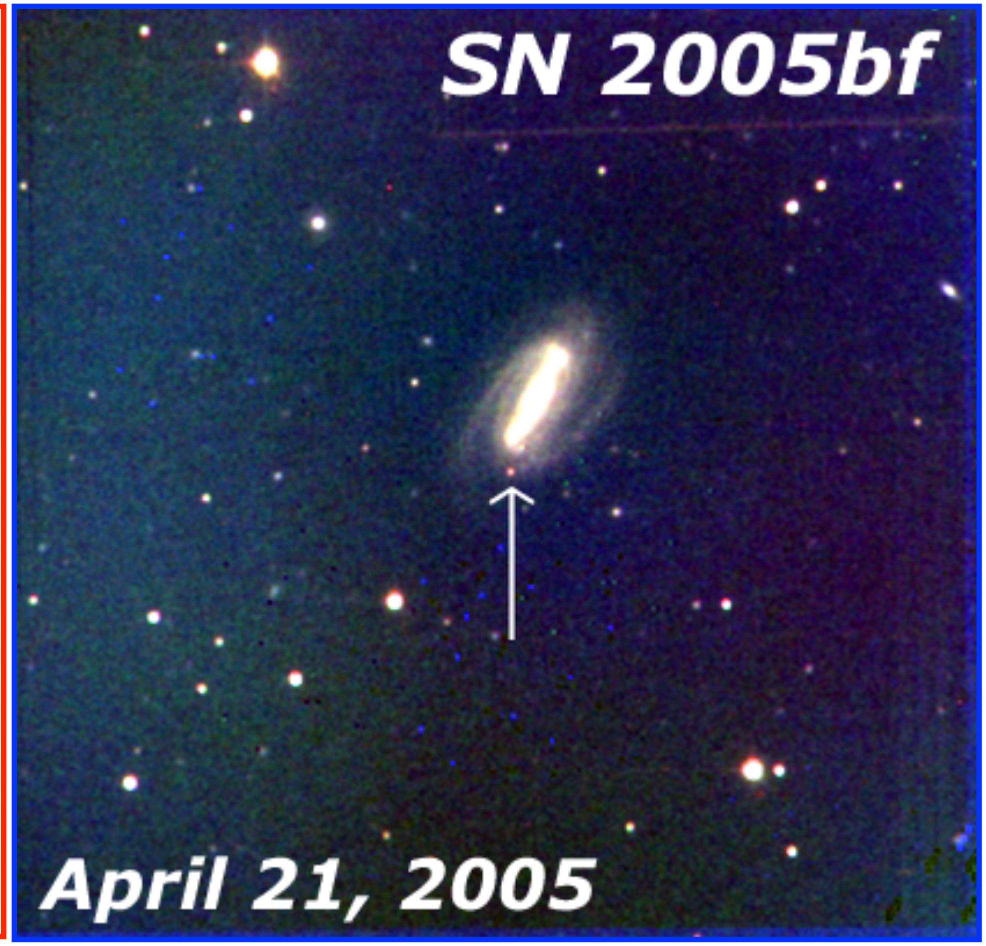
cse.ssl.berkeley.edu/



Type II core collapse supernova

BLUE - UV GREEN - B RED - I

Caltech Core Collapse Project (CCCP)



Type Ib/c core collapse supernova

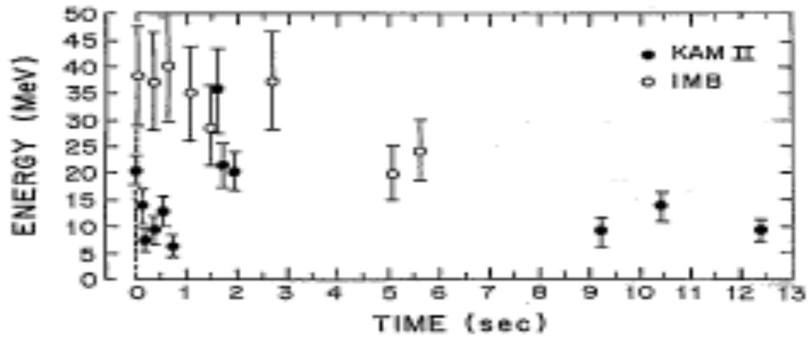
www.cfa.harvard.edu/ ~mmodjaz

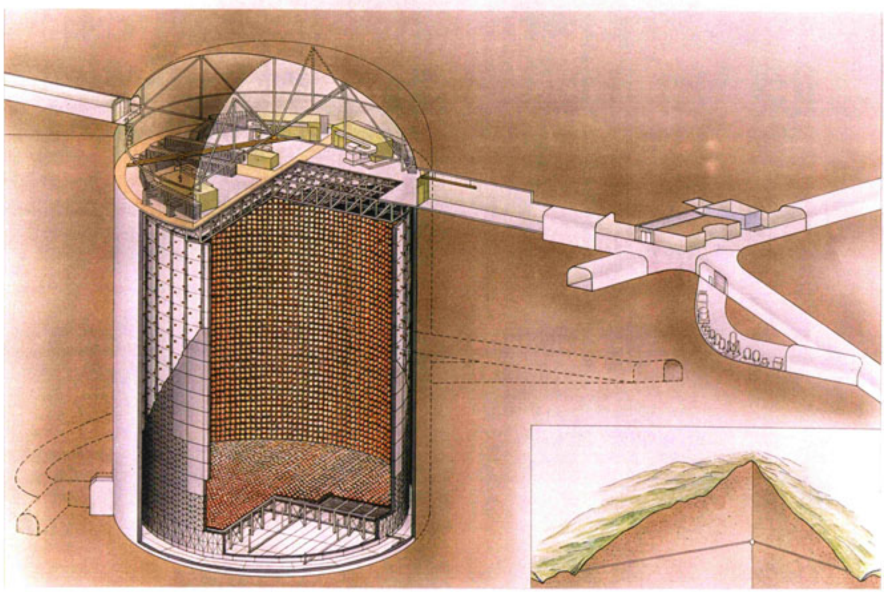
SN1987A

Tarantula Nebula in the Large Magellanic Cloud
(50 kpc)

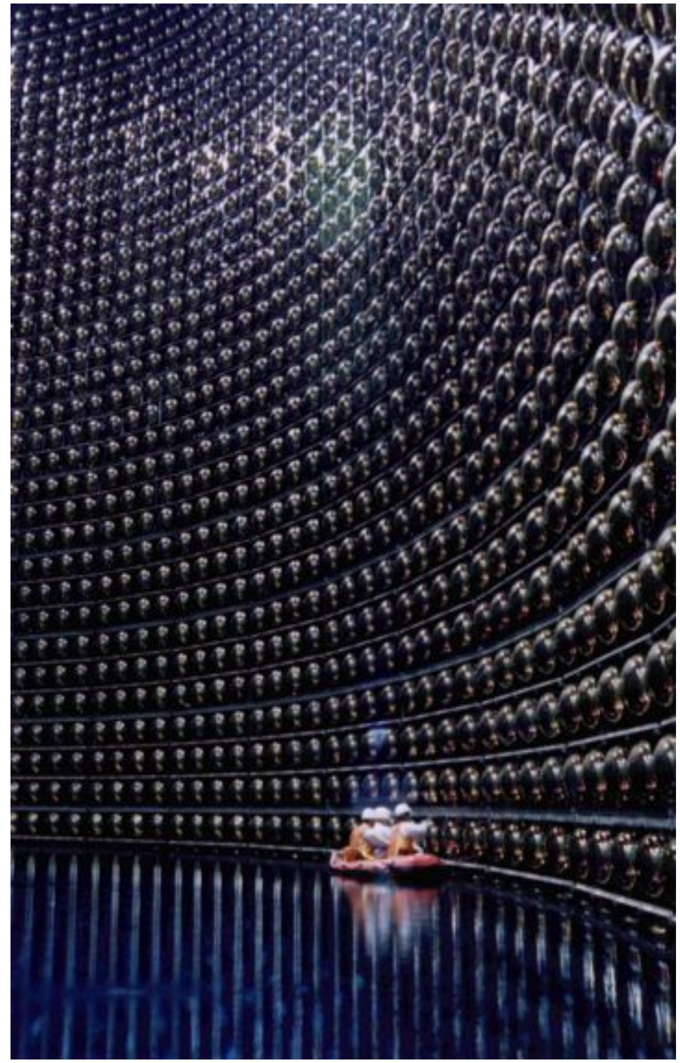
Observing Supernova Neutrinos

SN 1987A

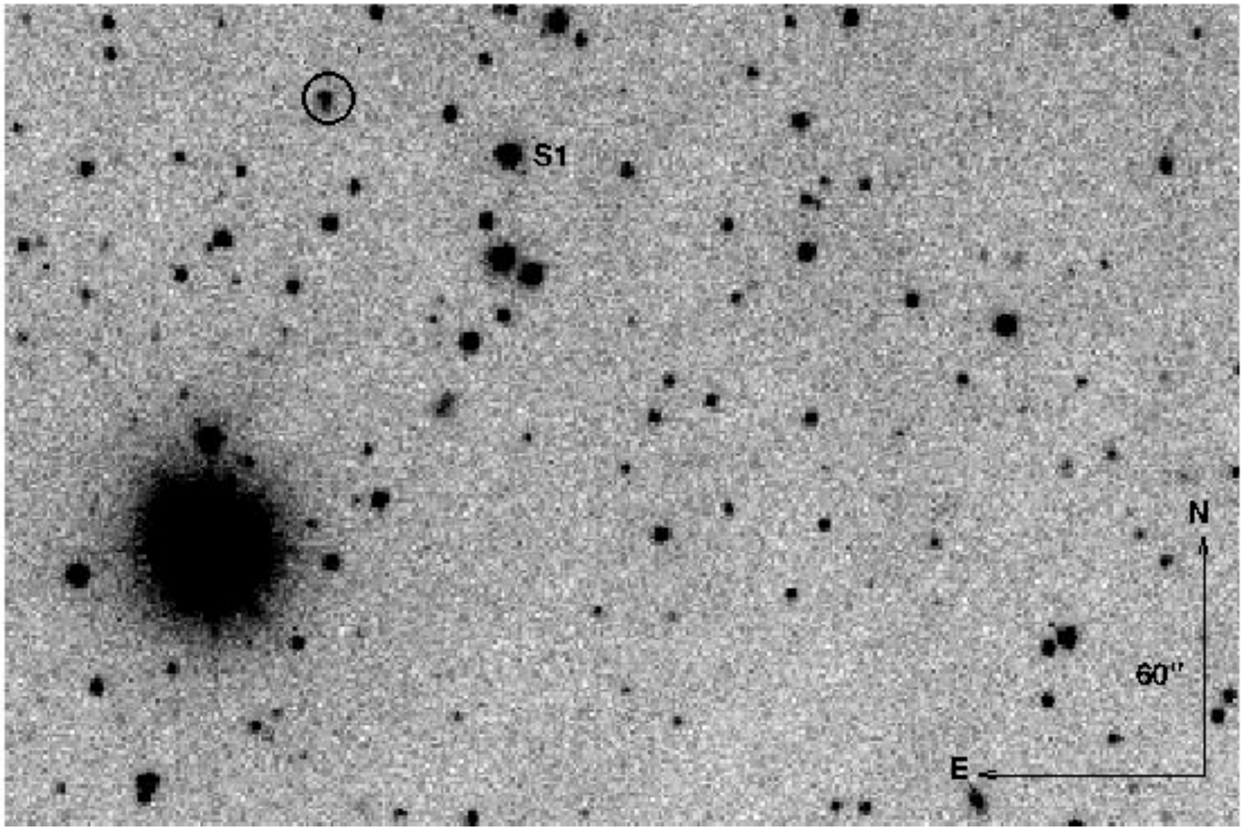




SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO NIKKEN SEKKEI



SN 2012ck – A. V. Fillipenko's KAIT survey, 19 May, 2012



PSN J19192793+4414509
RA: 19:19:27.93
Dec: +44:14:50.9
(J2000.0)

S1 –> SN:
43.14" E, 12.77" N

Electronic Telegram No. 3121SUPERNOVAE 2012ck IN anonymous galaxyCentral Bureau for Astronomical TelegramsINTERNATIONAL ASTRONOMICAL UNIONCBAT Director: Daniel W. E. Green; Hoffman Lab 209; Harvard University; 20 Oxford St.; Cambridge, MA 02138; U.S.A.e-mail: cbatiau@eps.harvard.edu (alternate cbat@iau.org)URL http://www.cbat.eps.harvard.edu/index.html Prepared using the Tamkin Foundation Computer NetworkSUPERNOVA 2012ck = PSN J19192793+4414509 Further to CBET 3111, M. Kandrashoff, K. Fuller, S. B. Cenko, W. Li, and A. V. Filippenko report the LOSS discovery of an apparent supernova onunfiltered KAIT images: SN 2012 UT R.A. (2000.0) Decl. Mag. Offset 2012ck May 19.47 19 19 27.93 +44 14 50.9 17.9 1".1 E, 1".7 NAdditional KAIT magnitudes for2012ck: May 15.50 UT, [18.8; 20.47, 17.9.

Figure of Merit:

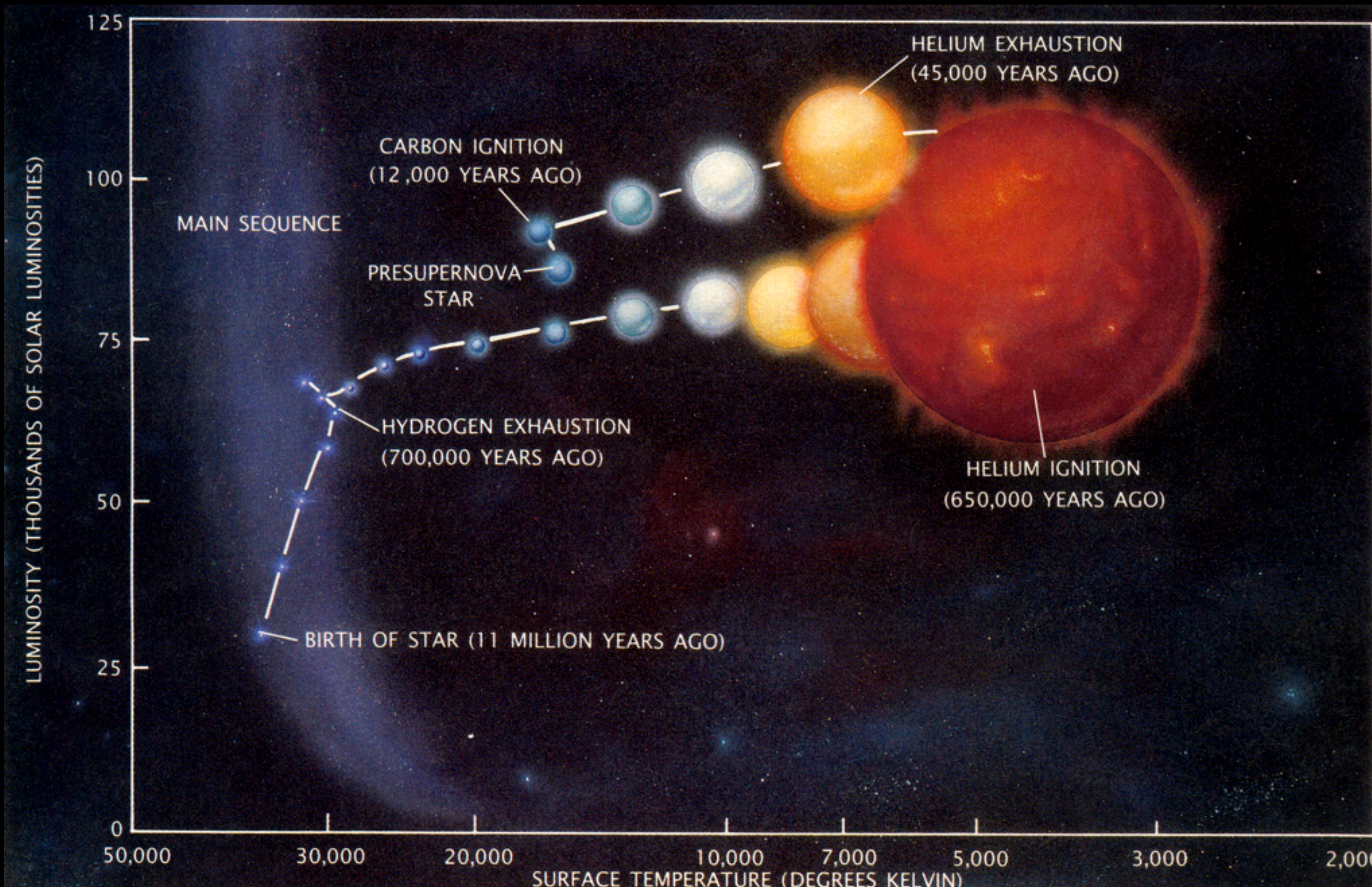
a core collapse per galaxy every 30 years

$$\text{SN rate} \quad \sim 10^{-9}\,\text{galaxy}^{-1}\,\text{s}^{-1}$$

$$\sim 1 \text{ galaxy per Mpc}^3$$

$$\text{causal horizon size} \;\sim 3000\,\text{Mpc}$$

$$\Rightarrow \quad 10 \text{ core collapses per second in universe}$$



Weaver & Woosley, *Sci Am*, 1987

Nuclear Burning Stages of a 25 M_{sun} Star

Burning Stage	Temperature	Density	Time Scale
Hydrogen	5 keV	5 g cm^{-3}	7 X 10^6 years
Helium	20 keV	700 g cm^{-3}	5 X 10^5 years
Carbon	80 keV	2 X 10^5 g cm^{-3}	600 years
Neon	150 keV	4 X 10^6 g cm^{-3}	1 year
Oxygen	200 keV	10^7 g cm^{-3}	6 months
Silicon	350 keV	3 X 10^7 g cm^{-3}	1 day
Core Collapse	700 keV ↓	4 X 10^9 g cm^{-3} ↓	~ seconds of order the free fall time
"Bounce"	~ 2 MeV	~10^{15} g cm^{-3}	~milli-seconds
Neutron Star	< 70 MeV initial ~ keV "cold"	~10^{15} g cm^{-3}	initial cooling ~ 15-20 seconds ~ thousands of years

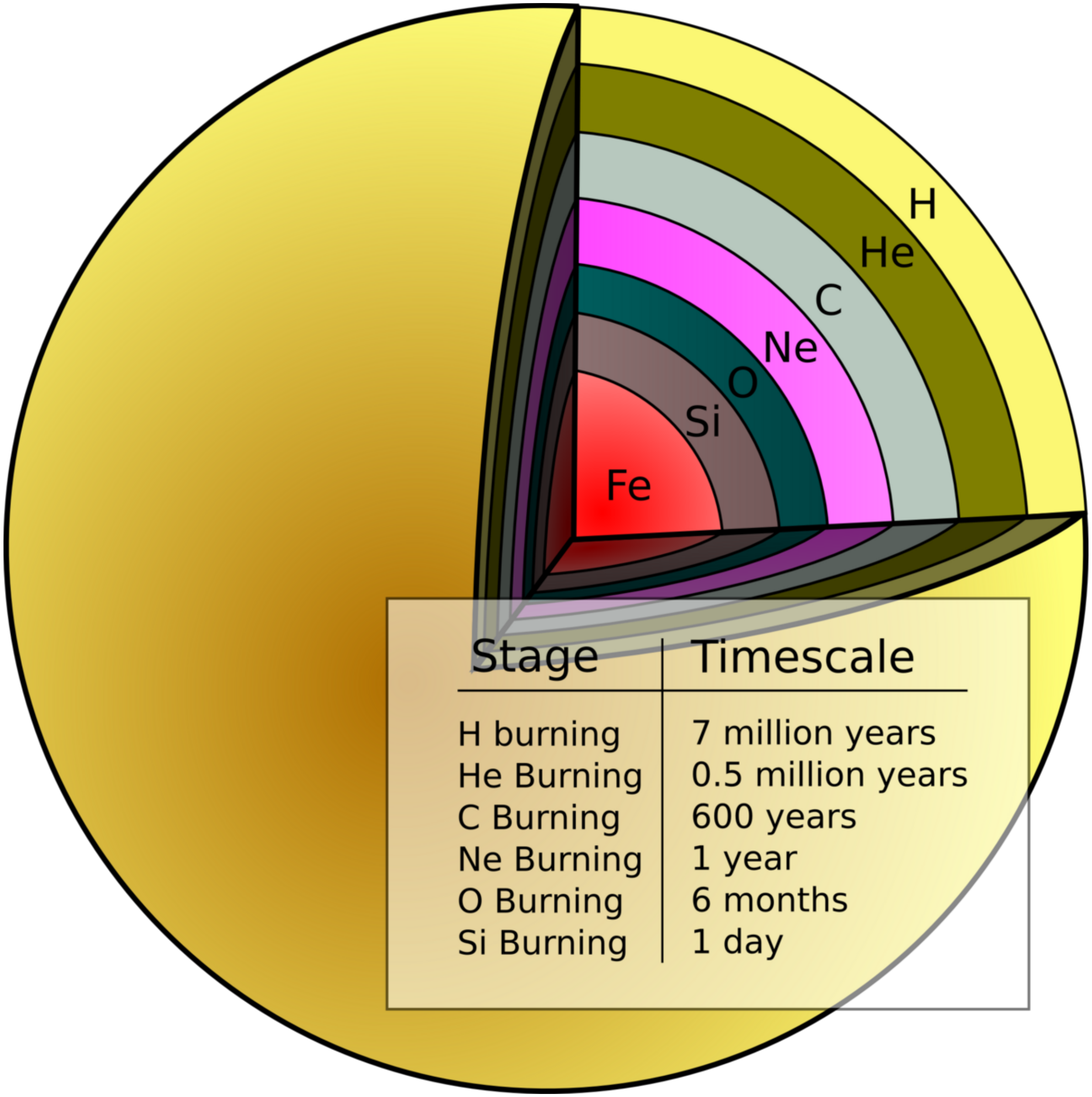
Massive Stars are Giant Refrigerators

From core carbon/oxygen burning onward
the neutrino luminosity exceeds the photon luminosity.

Neutrinos carry energy/entropy away from the core!

Core goes from $S/k \sim 10$ on the Main Sequence (hydrogen burning)
to a thermodynamically cold $S/k \sim 1$ at the onset of collapse!

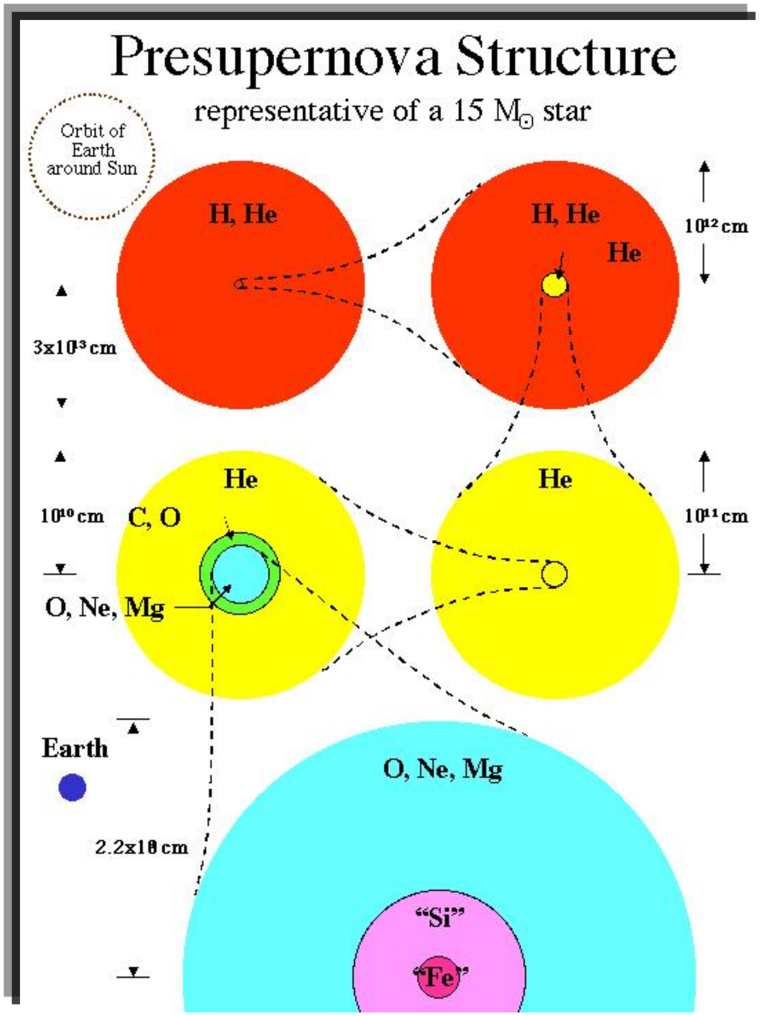
e.g., the collapsing core of a supernova can be a
frozen (Coulomb) crystalline solid with a
temperature ~1 MeV!



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

http://large.stanford.edu/courses/2008/ph204/deaconu1/

Structure of an Evolved Massive Star



Relevant Time Scales:

⇨ **Massive stars evolve for millions of years.**
⇨ **Die in a few hours in a supernova.**
⇨ **Explosion initiated in < 1 second.**

Relevant Spatial Scales:

⇨ **Iron core is roughly of Earth's size.**
⇨ **Outer stellar radius is larger than the orbit of the Earth around the Sun.**

"Fe" core is size of earth (~ 10^8 cm) and roughly the mass of the sun, with an entropy s/k ~ 1

Neutrinos Dominate the Energetics of Core Collapse Supernovae

Explosion
only ~1% of neutrino energy

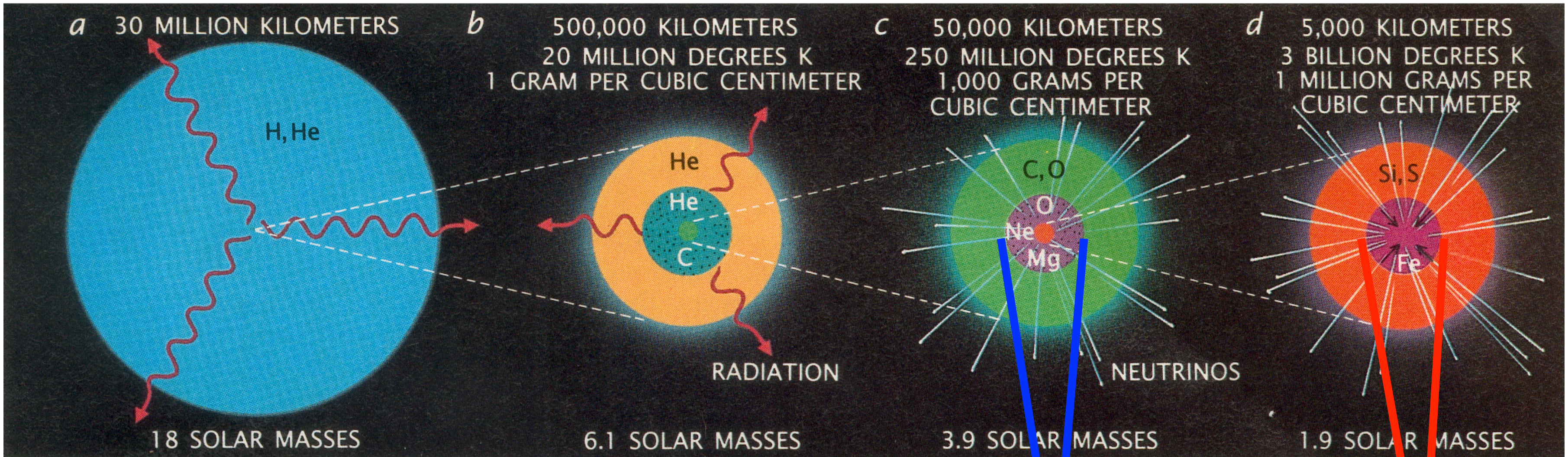
- Total optical + kinetic energy, 10^{51} ergs
- Total energy released in Neutrinos, 10^{53} ergs

10% of star's rest mass!

$$E_{\mathrm{GRAV}} \approx \frac{3}{5}\frac{G\,M_{\mathrm{NS}}^2}{R_{\mathrm{NS}}} \approx 3\times10^{53}\,\mathrm{ergs}\left[\frac{M_{\mathrm{NS}}}{1.4\mathrm{M}_{\mathrm{sun}}}\right]^2\left[\frac{10\ \mathrm{km}}{R_{\mathrm{NS}}}\right]$$

Neutrino diffusion time, $\tau_\nu \approx 2\ \mathrm{s}$ to $10\ \mathrm{s}$

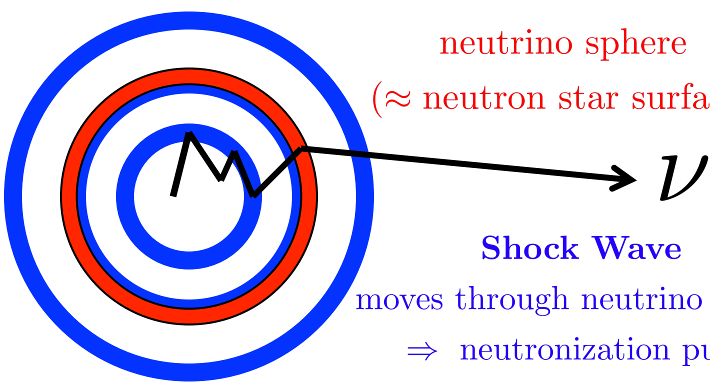
$$L_\nu \approx \frac{1}{6}\frac{GM_{\mathrm{NS}}^2}{R_{\mathrm{NS}}}\frac{1}{\tau_\nu} \approx 4\times10^{51}\,\mathrm{ergs\ s^{-1}}$$



ν self coupling – induced
collective oscillations, spectral swaps
at shock breakout, neutronization pulse,
$L_\nu \sim 10^{53}\,\mathrm{erg\,s^{-1}}$

O – Ne – Mg
Core Collapse
$8 - 12\,\mathrm{M}_\odot$

Fe (iron)
Core Collapse
$> 12\,\mathrm{M}_\odot$



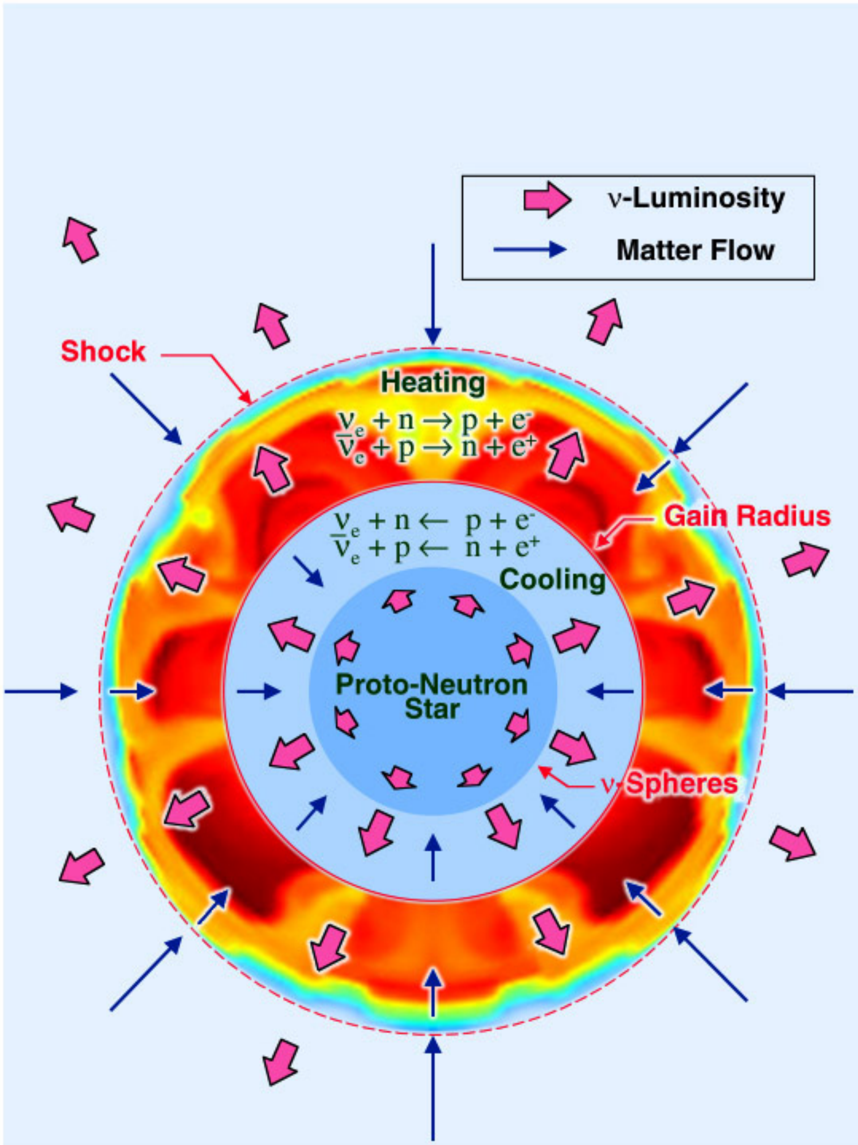
neutrino sphere
(≈ neutron star surface)

Shock Wave
moves through neutrino sphere
⇒ neutronization pulse

ν_e flux $\gg$ $\bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ fluxes

ν self coupling – induced
collective oscillations, spectral swaps
at late times, $t_{\mathrm{pb}} > 3\,\mathrm{s}$,
$L_\nu \sim 10^{51}\,\mathrm{erg\,s^{-1}}$

The Role of Core Fluid Instabilities



Possible Instabilities:

⇨ **Convection (e.g., Ledoux)**

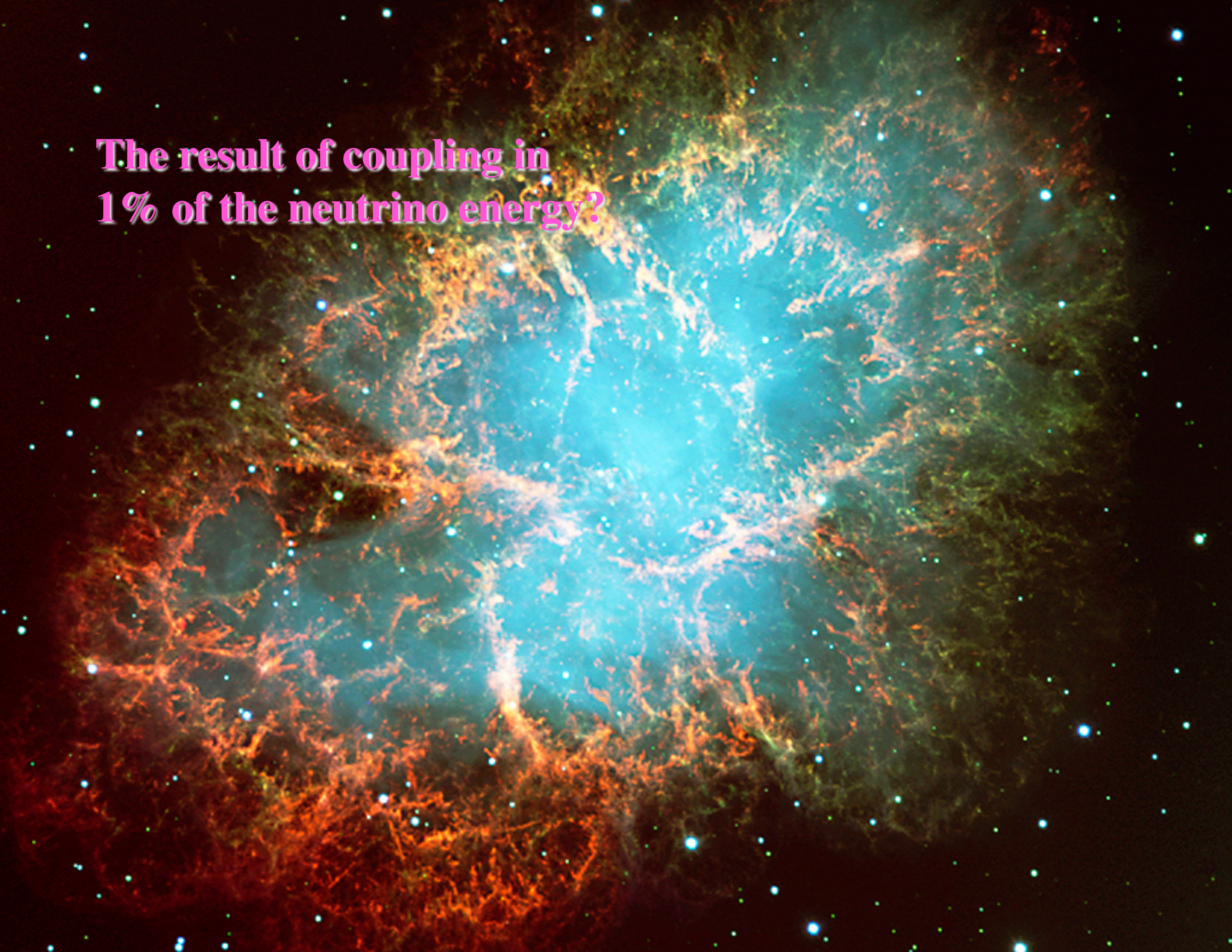
Negative gradients in entropy, lepton fraction, or both.

⇨ **Doubly Diffusive Instabilities (e.g., Neutron Fingers, LEF)**

Crossed gradients in entropy and lepton fraction.

⇨ **Shock Wave Instability**

Something completely different.


The result of coupling in
1% of the neutrino energy?

The Core Collapse Supernova Phenomenon is Exquisitely Sensitive to Flavor Changing Processes and New Neutrino Physics:

- Gravitational collapse results in high electron and ν_e Fermi Energies (representing ~ 10^{57} units of e-lepton number); μ/τ charged leptons are absent and the corresponding neutrinos are pair-produced so they carry no net lepton number.
  Any process that changes flavor $\nu_e \rightarrow \nu_{\mu/\tau/s}$ will open phase space for electron capture as well as reducing e-lepton number.

- Later, energy (10% of the core's rest mass) is in seas of active neutrinos of all flavors. Entropy and lepton number transported by neutrinos.

- Neutron/proton ratio (crucial for nucleosynthesis) and energy deposition determined by:

$$\nu_e + n \rightleftharpoons p + e^- \qquad \bar{\nu}_e + p \rightleftharpoons n + e^+$$

Neutrino Flavor Oscillations

The advent of supercomputers has allowed us in the last few years to follow neutrino flavor transformation in core collapse supernovae, including the first self-consistent treatment of **nonlinearity** stemming from neutrino-neutrino forward scattering.

The results are startling. Despite the small measured neutrino mass-squared differences, **collective** neutrino flavor transformation can take place deep in the supernova envelope;

~~MSW~~ does not work in some important regimes in supernovae.

I will show work done in the UCSD/LANL collaboration
(Carlson, Cherry, Duan, Friedland, Fuller, Qian and others)
but there are many groups (e.g., Raffelt, Hannestad, Mirizi,
Smirnov, etc.) around the world which also
address the issues discussed here with broadly similar results.

This is an area of intense research right now,
but I will emphasize the consensus on supernova neutrino flavor
evolution which has emerged so far.

Instead we discovered something very different . . .
H. Duan, G. Fuller, J. Carlson, Y.-Z. Qian, PRD D74, 105014 (2006)

A phenomenon which can occur in many different environments in the different varieties of core collapse supernova :

The neutrino **spectral swap/split**.

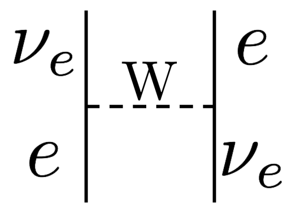
This phenomenon produces a distinctive signature in a supernova neutrino burst signal which, if detected, is usually a dead give away for the neutrino mass hierarchy.

Coherent Flavor Evolution for Neutrino i

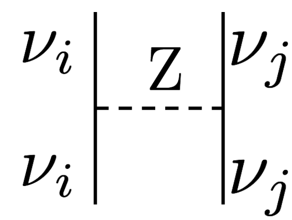
$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_{\mathrm{e}} \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

$$i\,\frac{\partial}{\partial t}\,\psi_{\nu,i} \;=\; \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i}\right)\psi_{\nu,i}$$

neutrino-electron
charged current
forward exchange
scattering



neutrino-neutrino
neutral current
forward scattering



Neutrino Self Coupling - the source of nonlinearity

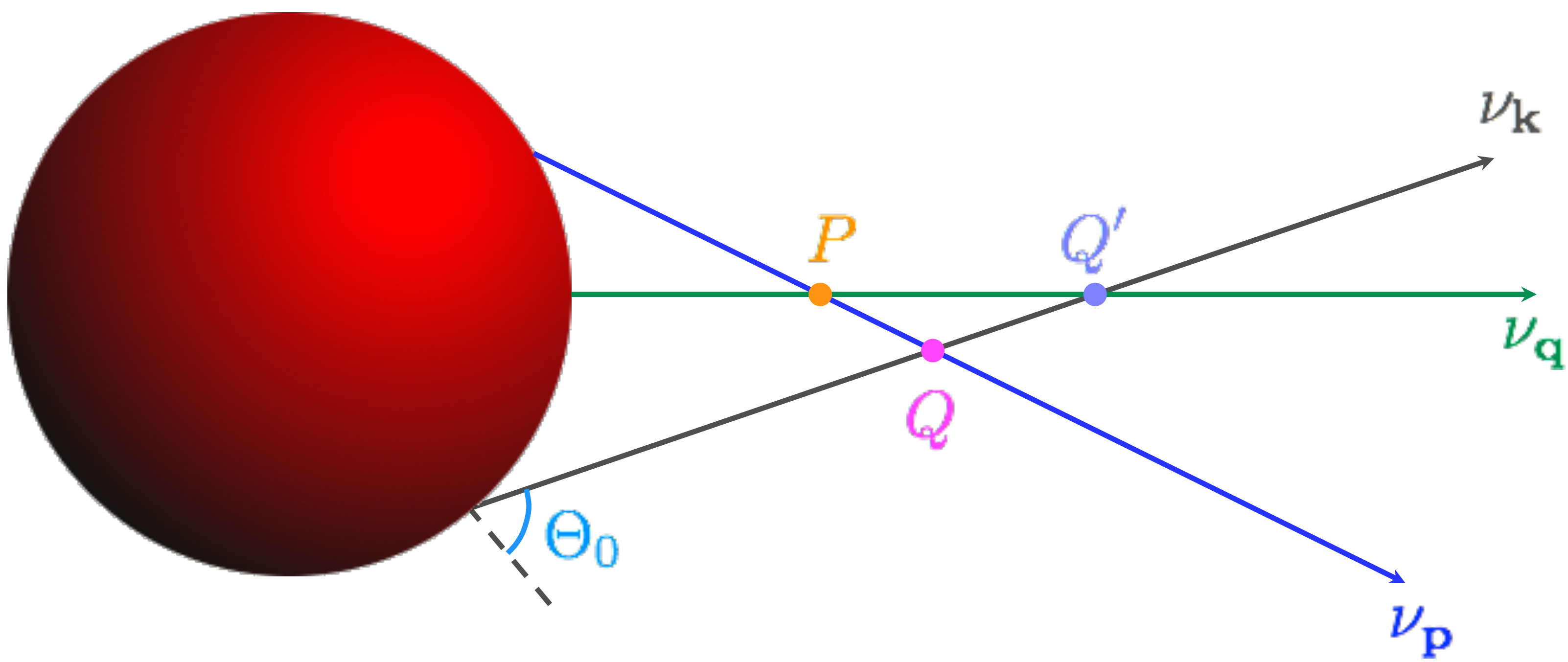
$$\mathcal{H}_{\nu\nu,i} \equiv \sqrt{2}G_{\mathrm{F}} \sum_j \left(1 - \hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_j\right) n_{\nu,j}\,\psi_{\nu,j}\psi^\dagger_{\nu,j}$$

$$-\sqrt{2}G_{\mathrm{F}} \sum_j \left(1 - \hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_j\right) n_{\bar{\nu},j}\,\psi_{\bar{\nu},j}\psi^\dagger_{\bar{\nu},j}$$

now self-consistently couple flavor evolution

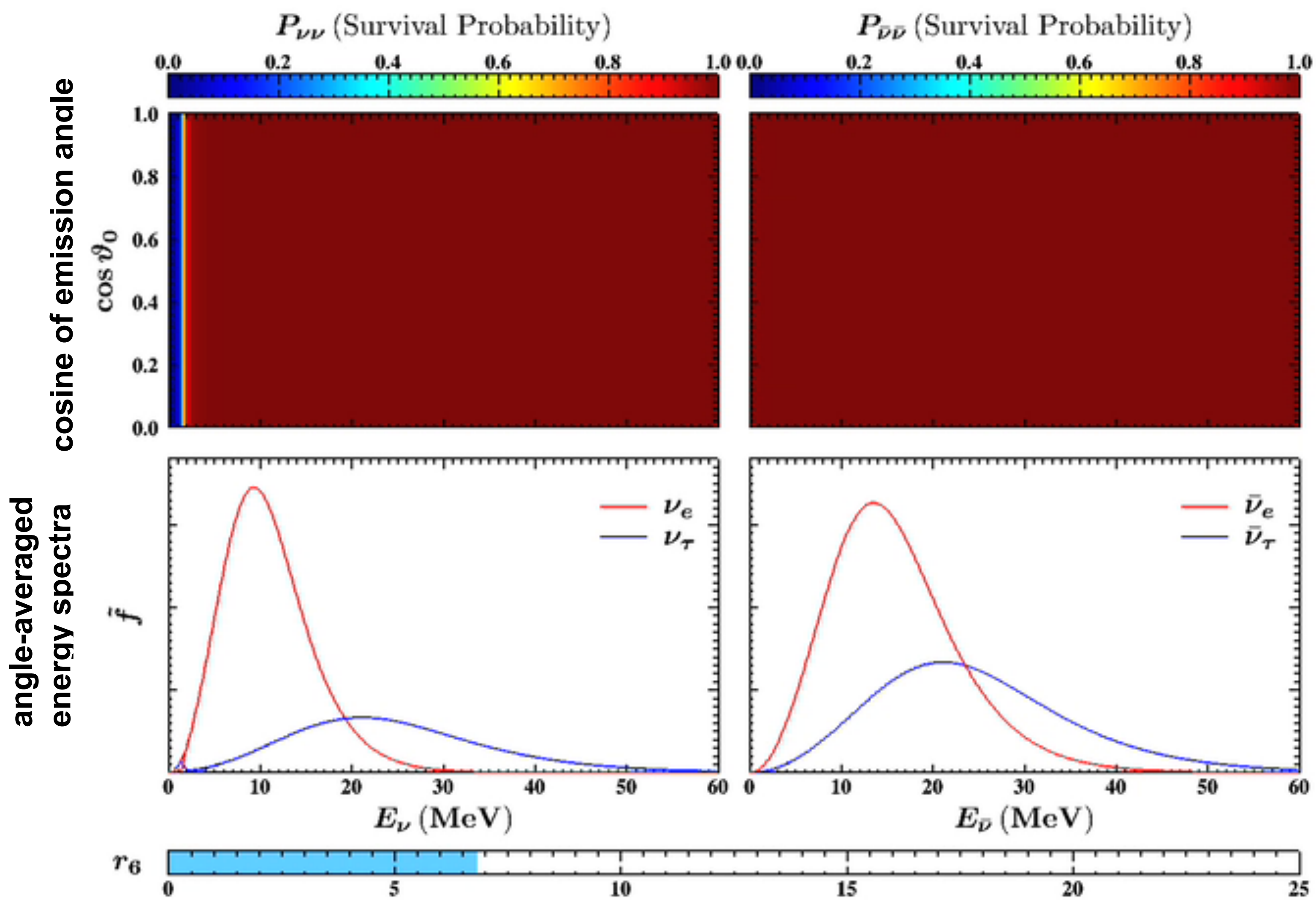
on all neutrino trajectories . . .

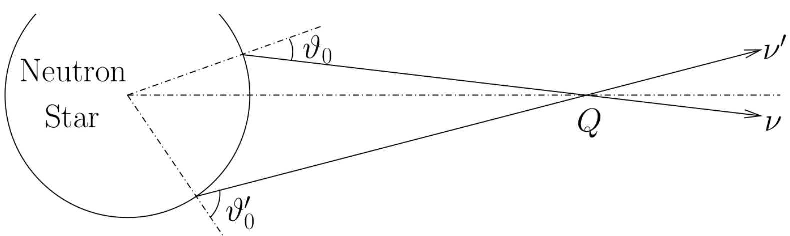
- Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories



Must solve many *millions* of coupled, nonlinear partial differential equations!!

neutrinos $\nu_e \rightleftharpoons \nu_\tau$ **antineutrinos** $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$

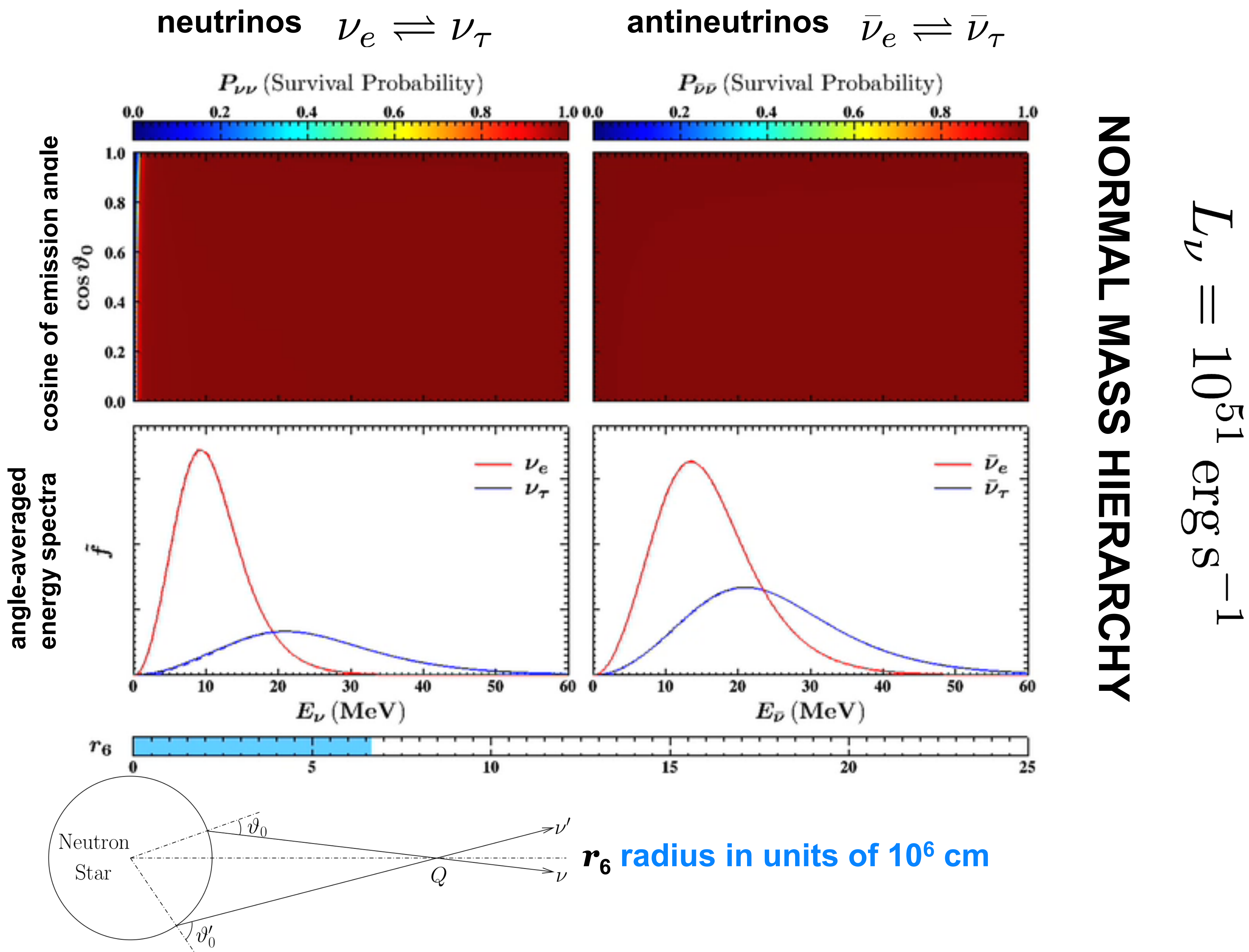


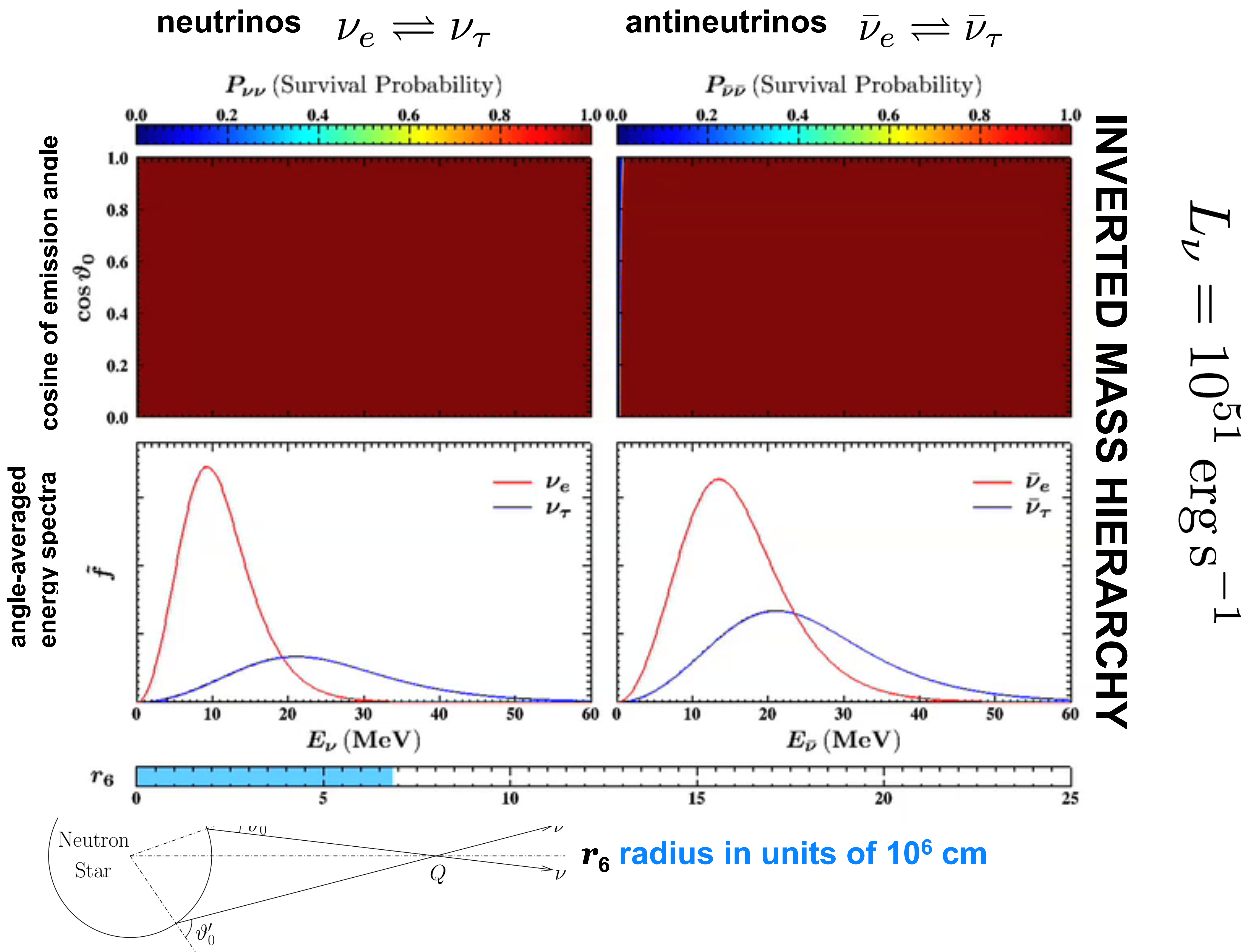


r_6 radius in units of 10^6 cm

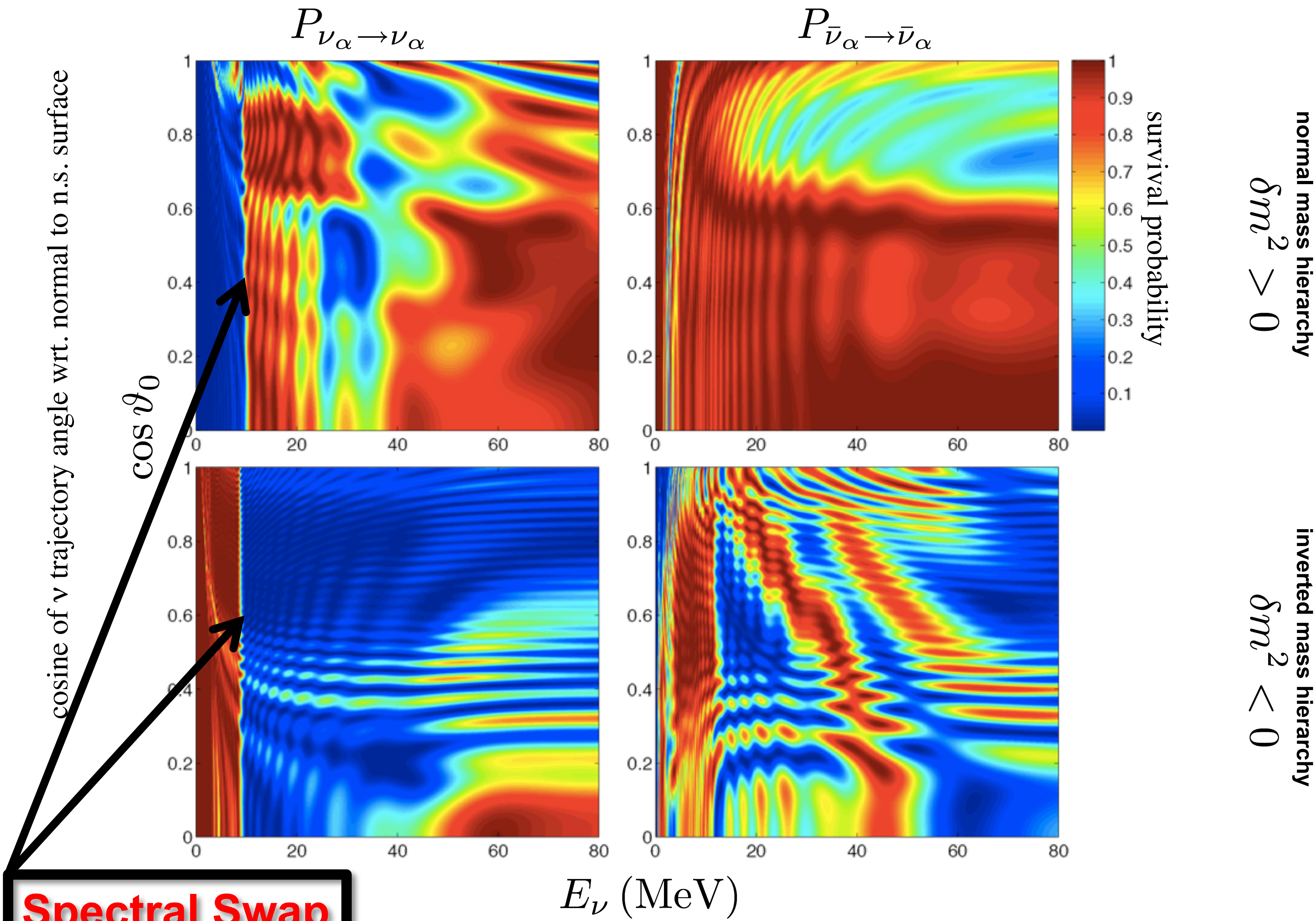
NORMAL MASS HIERARCHY

$L_\nu = 0$


neutrinos $\nu_e \rightleftharpoons \nu_\tau$
antineutrinos $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$
$P_{\nu\nu}$ (Survival Probability)
$P_{\bar{\nu}\bar{\nu}}$ (Survival Probability)
cosine of emission angle
$\cos\vartheta_0$
angle-averaged energy spectra
$\tilde{f}$
E_ν (MeV)
$E_{\bar{\nu}}$ (MeV)
r_6
Neutron Star
Q
NORMAL MASS HIERARCHY
$L_\nu = 10^{51}\,\mathrm{erg\,s^{-1}}$
r_6 radius in units of 10^6 cm



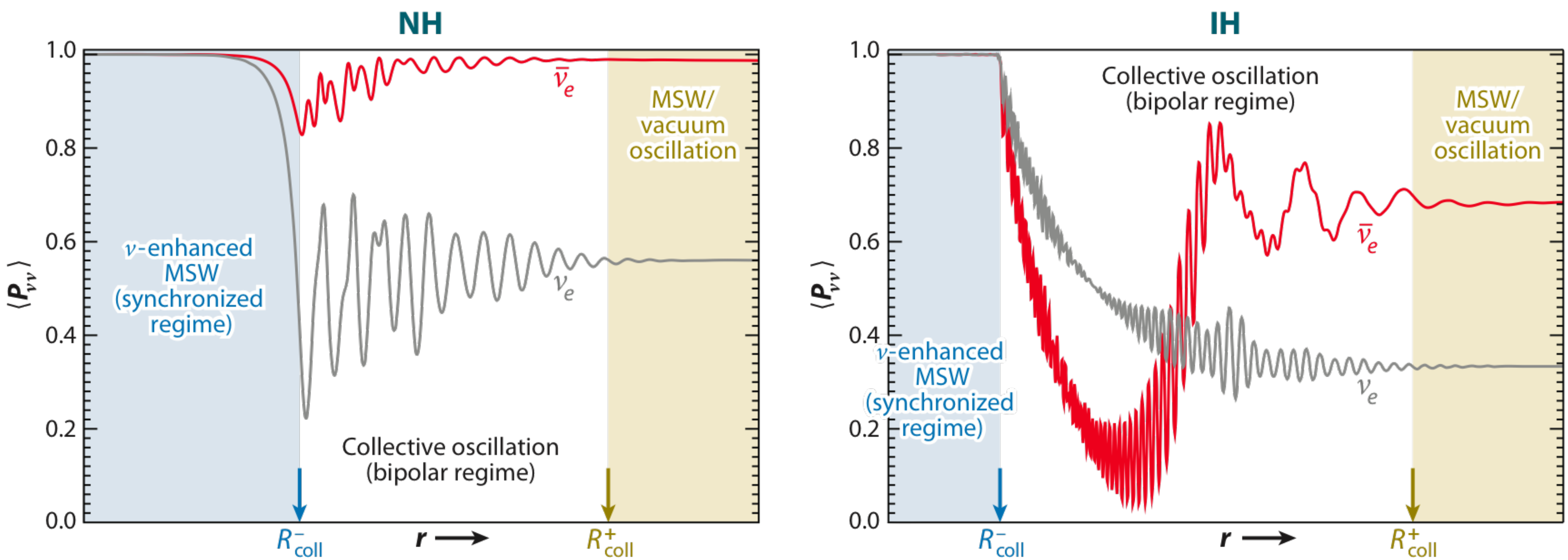
neutrinos $\nu_e \rightleftharpoons \nu_\tau$
antineutrinos $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$
$P_{\nu\nu}$ (Survival Probability)
$P_{\bar{\nu}\bar{\nu}}$ (Survival Probability)
0.0 0.2 0.4 0.6 0.8 1.0
cosine of emission angle
$\cos\vartheta_0$
angle-averaged energy spectra
$\bar{f}$
ν_e
ν_τ
$\bar{\nu}_e$
$\bar{\nu}_\tau$
E_ν (MeV)
$E_{\bar{\nu}}$ (MeV)
0 10 20 30 40 50 60
r_6
0 5 10 15 20 25
Neutron Star
ϑ_0
ϑ_0'
Q
ν
r_6 radius in units of 10^6 cm
INVERTED MASS HIERARCHY
$L_\nu = 10^{51}\ \mathrm{erg\ s^{-1}}$



consequences of neutrino mass and quantum coherence in supernovae

H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) **astro-ph/0606616**

Neutrino Oscillation Regimes in Core Collapse Supernovae



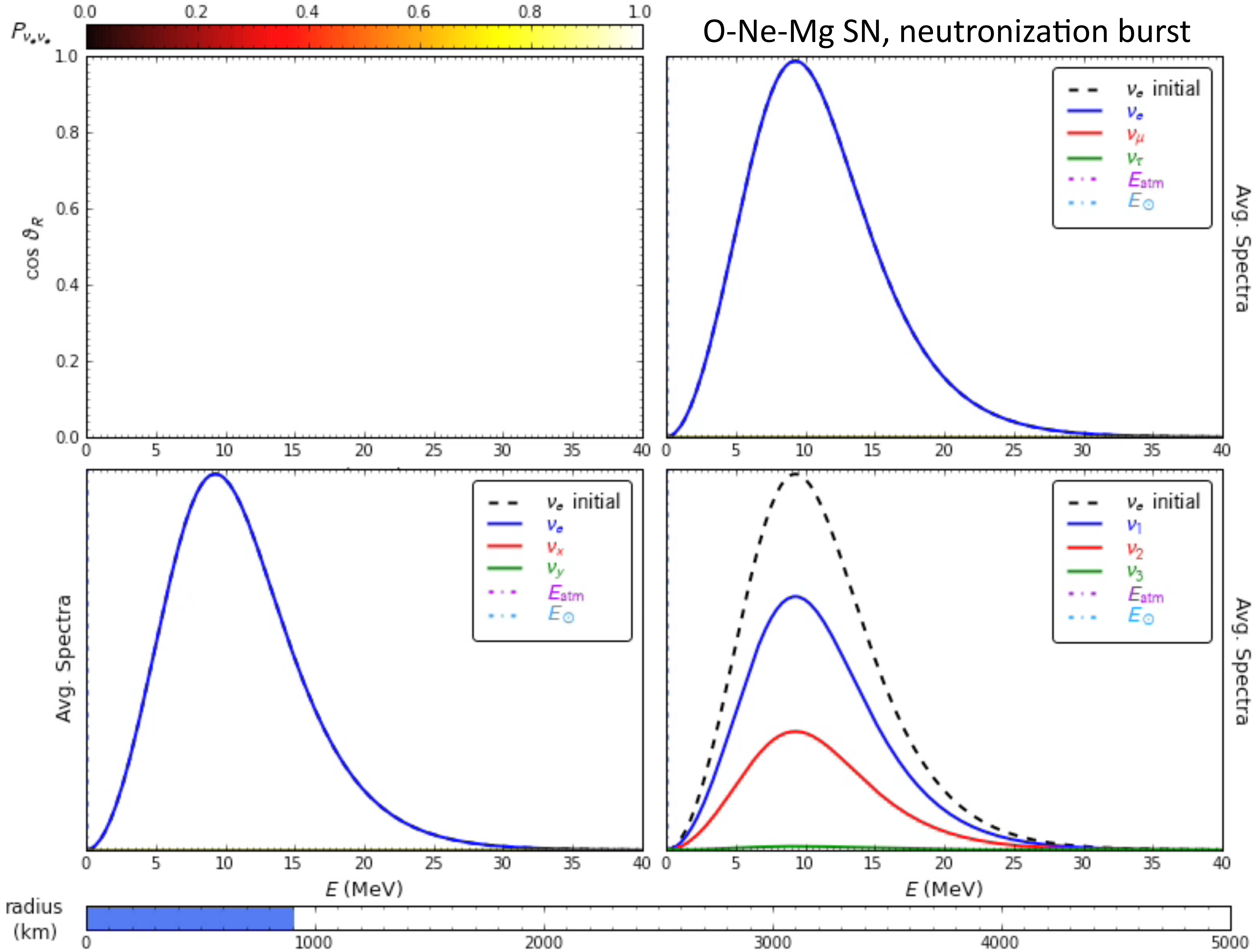
Duan, Huaiyu, et al. 2010.
Annu. Rev. Nucl. Part. Sci 60:569–594.

Though core collapse supernovae are very complicated and have various epochs/environments with vastly different values of neutrino energy spectra/fluxes and matter densities/distributions, we find this swap phenomenon in many of them.

Think of the earth's atmosphere: very complicated, with water vapor and solar heating, and radiation transport, and the ocean, all played out on the surface of a rotating sphere. Nevertheless, there are phenomena like thunderstorms which occur and which have a life and characteristics of their own, independent of the model for the atmosphere . . .

The neutrino spectral swap may be like this.

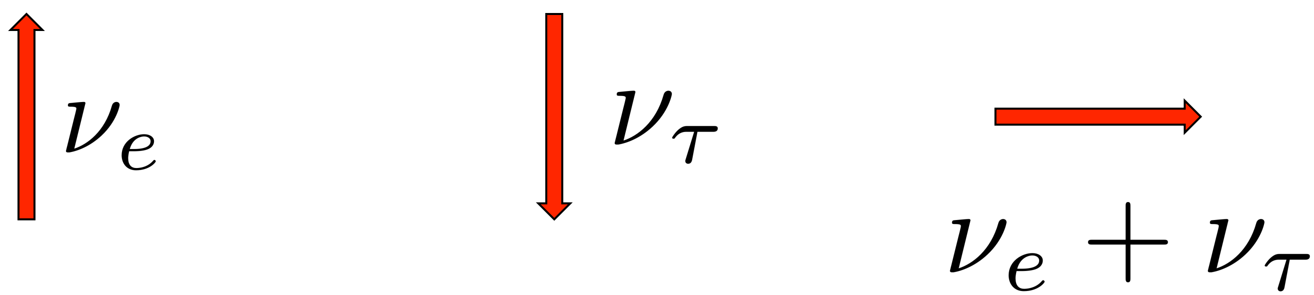
O-Ne-Mg SN, neutronization burst



Swap Phenomenon seems to be ubiquitous

Can understand this if we associate a "spin" with the neutrino's flavor:

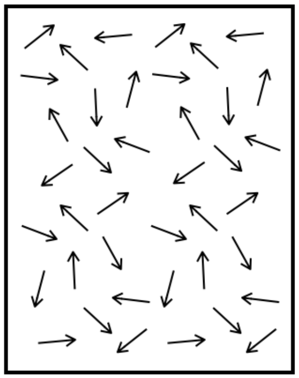
The direction of this "spin" gives the flavor, *e.g.,*



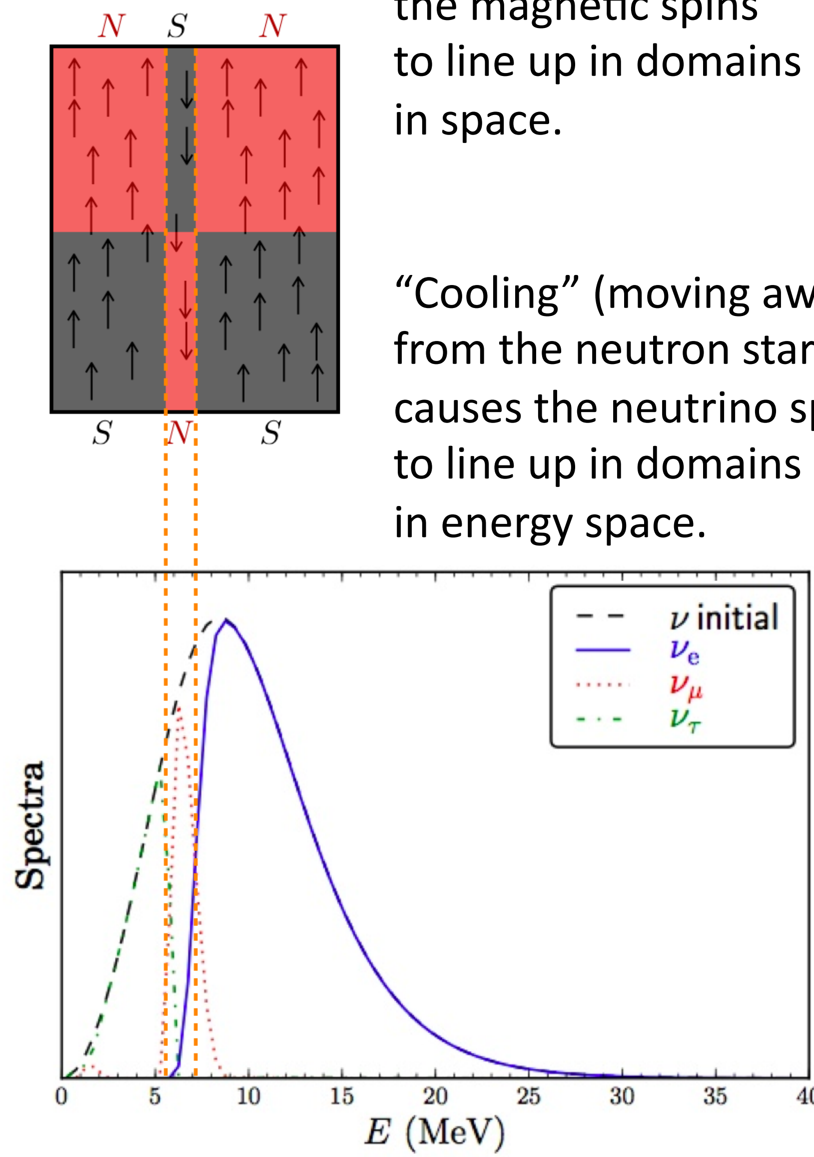
analogy: magnetic (moment) spins of atoms

Magnetic Analogy

$T > T_C$



$T < T_C$



Cooling causes
the magnetic spins
to line up in domains
in space.

"Cooling" (moving away
from the neutron star)
causes the neutrino spins
to line up in domains
in energy space.